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EXPERIMENTAL INVESTIGATION OF WIRE EDM PARAMETERS FOR GEAR CUTTING PROCESS USING DESIRABILITY WITH PCA

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ABSTRACT: Wire EDM, the Wire Electric Discharge Machining is a variant of EDM and is commonly known as wire cutting or wire-cut EDM. Gear cutting in wire EDM plays an important role in day to day life and it has found the applications in various automobile industries, aerospace industries, and in various electrical equipments etc. The present work deals with the analysis and optimization of a high quality miniature spur gear and the gear is made of copper. The wire is made of brass and has a diameter of 0.25mm. The gear has a pitch circle diameter of 20mm, pressure angle of 20^0, addendum diameter of 24.44mm, duodenum diameter of 14.44mm and number of teeth to be cut is 9. A Taguchi L9 orthogonal array is being created and the input combinations were obtained to calculate the output results. Pulse on time, Pulse off time and wire tension are the 3 process parameters chosen at 3 different levels each and the 3 output parameters i.e. MRR, surface roughness and kerf width obtained were optimized using Desirability with PCA technique. ANOVA table is obtained to know which factor significantly affects the wire EDM parameters the most. Various graphs and plots have been obtained to investigate the effects of wire EDM process parameters. The graph obtained is analyzed and optimized to know the best results. The result obtained was further investigated to produce large quality of miniature spur gears.
Keywords: Wire EDM, Gear cutting, Pitch circle diameter, PCA, Spur gears

I. INTRODUCTION

Wire EDM also known as spark eroding, wire erosion or wire burning is an industrialized process in which the material is removed from the work-piece by the help of the wire made of brass and a new desired shape is obtained by repetitive sparks produced by the electric voltage and distilled water as dielectric fluid. The first wire EDM machine came online in the 1960s, however the actual dates back to the 18th century. Joseph Priestley, an English scientist and a chemist philosopher in 1770 discovered electrical discharge that could erode the metal. In 1943, two scientists named B.R. Lazarenko and N.I. Lazarenko found a method that would harness the power of electrical discharge for different manufacturing processes. In 1967, the first EDM machine became commercially available that uses wire as an electrode. In the mid 1980s the techniques of the EDM were transferred to a machine tool. This change made EDM more widely acceptable over traditional machining process. In wire EDM, different types of wires can be used for cutting purposes like brass wire, tungsten wire, copper wire, molybdenum wire, out of which brass wire is used as the most because of its low cost, reasonable conductivity, improved flush-ability and high tensile strength. The machine consists of a pump, a system, a stabilizer, single stranded wires and nozzles for flushing. The wire which is constantly fed from the spool is held between upper and lower guides. The wire diameter is basically 0.25 mm. The guides generally moves in the X-Y plane and sometimes the upper guide can also move independently giving rise to various shapes like square at the top or circle at the bottom. This gives the wire EDM the ability to be programmed to cut very intricate and delicate shapes. When the wire is in conjunction with the work-piece, a discontinuous sparks is produced that allows the metal to cut by the help of electric current and voltage produced. Flushing is important in wire EDM. The distilled water used acts as a dielectric that allows the cut debris to flow away from the work-piece and it also act as a coolant. The water flows along the wire both from upper and lower guides to maintain the stability and uniform cutting in the wire. Water resistivity and other electrical properties were also controlled by filters and deionizer units. The schematic diagram and the process of wire EDM is shown in figure 1.

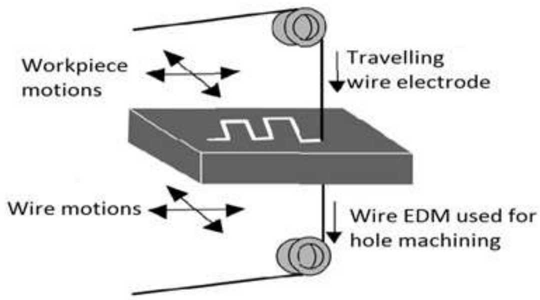

Figure 1: Schematic diagram of wire EDM process

Gear cutting in wire EDM is an important aspect of manufacturing process. A gear is a rotating machine part having teeth that meshes with other toothed part to transmit torque. The gears are of different types like spur gears, helical gears, bevel gears etc. Stainless steel and copper are the most widely used materials for machining of the gears. Different types of gear processes include gear hobbing, broaching, grinding and milling. In wire EDM the gears are cut with proper accuracy and precision. Different types of wires are being used to cut different types of gears in order to achieve good finish. The gear has found its applications in many industries including electrical, aerospace, thermal industries, biomedical and automobile industries etc. In the past few years, the technology in the gears has taken a drastically improvement in different engineering fields.

II. LITERATURE REVIEW

The development and works in wire EDM has now became an important aspect in several fields as several types of works have been carried out in the wire EDM machine. Different types of research work have been proposed and carried out by different authors, however still experiments are being conducted to optimize the parameters by several new optimization techniques. Spedding and Wang, 1997 [1] developed a model of WEDM process by using response surface methodology and artificial neural networks and initiate that the model exactness of both was better. Lin et al., 2001 [2] created a control strategy so that the accuracy of the corner parts is improved in the wire EDM process based on Fuzzy logic. Jahan et al., 2009 [3] investigated using transistor and RC typed generators in order to find the effect of EDM machining. It was found that in RC type pulse generator the surface finish was found better rather than transistor type pulse generator. Saha et al., 2008 [4] developed a back propagation neural network model and regression model to find the cutting speed and surface roughness of tungsten carbide in wire EDM process. Lee and Li, 2003 [5] suggested that the surface integrity of the EDM machined surface remains intact, when the peak current is less than 16A. Tanimura and Heuvelman, 1977 [6] developed a short circuit detecting system, in which the chock inductance of the pulse generator is adjusted in order to avoid the sparks causing the wire to rupture. Toshun et al., 2004 [7] studied the kerf and material removal rate in wire electrical discharge machining based on Taguchi method. Kinoshita et al., 1982 [8] studied the various types of wire breakage. They created a control system in which they monitored the pulse frequency in order to prevent the wire breakage.

III. EXPERIMENTAL WORK

A. Experimental setup

The present work deals with the manufacturing of a spur gear made of copper of thickness 3mm of 20 cm in length and 10 cm in width. The experiment is carried out in an Ecocut Electronica ePulse machine and the wire material is made of brass. The diameter of the brass wire is 0.25mm in diameter and the dielectric fluid used is distilled water.

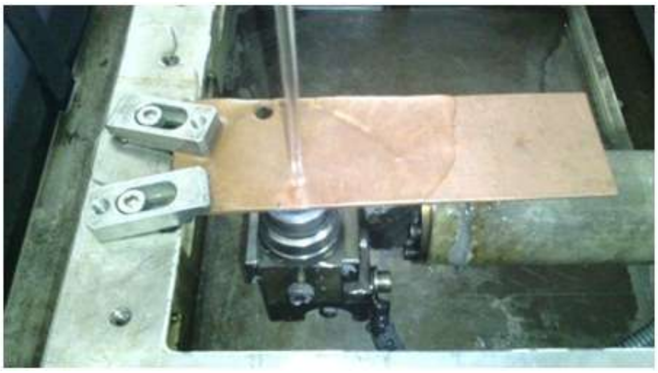

Figure 2: Cutting of copper plate in shape of a gear

Figure 2 depicts the cutting of a copper plate in shape of a gear by the wire EDM machine. The present work is carried out by taking input parameters such as Pulse on time (TON), Pulse off time (TOFF) and wire tension (WT). The three levels were chosen according to the machine constraints and different literature reviews. Appropriate data has been given to the machine like pitch circle diameter, number of teeth, pressure angle, addendum diameter etc. in order to obtain the gear. Further, the gear codes obtained from the software is been transferred to the machine for cutting operation. The values and ranges are set in such a way that it satisfies the minimum cutting condition of the gear without breakage of the wire. The values obtained from the suitable software are carried out for the experimentation. A total of 9 sets of experiments were carried out and the output parameters i.e. Material removal rate (MRR), Surface roughness (Ra) and Kerf width was measured accordingly.

Table 1: Different Parameters and ranges used for experimentation

Input Parameters	**Units**	**Symbol**	**Levels**		
			I	II	III
Pulse on time	µs	TON	110	115	120
Pulse off time	µs	TOFF	55	57	59
Wire tension	Kg-f	WT	5	6	7

The different parameters and ranges obtained in Table 1 is designed and assigned to the software "Minitab" in order to obtain L9 orthogonal array as shown in Table 3. The other values of EDM parameters like peak voltage, discharge current, water pressure, wire feed rate and servo voltage are kept constant and is shown in Table 2.

Table 2: Constant machine parameters used in the experiment

Input Parameters	**Peak Voltage(VP)**	**Peak current (IP)**	**Wire feed rate (WF)**	**Water pressure (WP)**	**Servo Voltage (SV)**
Units	V	A	m/min	Kg/cm2	V
Values	11	1	4	1	20

Some of the other gear specifications used for this experiment are Pitch circle diameter which is taken as 20mm, pressure angle 20^{0}, number of teeth as 9, base diameter as 18.79mm, duodenum diameter as 14.44mm, number of teeth for span as 2, addendum diameter as 24.44mm, tooth width of 3.49mm and base tangent length of 10.12mm. The profile is involute and the gear material is made of copper.

Table 3: L9 array orthogonal array obtained for different input and output responses

Sl	**Process parameters**			**Response parameters**		
	T_{ON}	T_{OFF}	W_T	MRR	Ra	Kerf

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number						width
1	110	55	5	2.186	2.34	0.257
2	110	57	6	2.032	2.36	0.256
3	110	59	7	1.998	1.78	0.258
4	115	55	6	2.347	2.67	0.266
5	115	57	7	2.096	2.43	0.254
6	115	59	5	2.018	2.52	0.251
7	120	55	7	1.918	1.89	0.272
8	120	57	5	2.643	2.20	0.264
9	120	59	6	2.326	2.03	0.268

B. Determining MRR, Surface roughness and Kerf width

1. Calculating MRR

The material removed from the work-piece is calculated in terms of MRR which is given by $MRR = Vc * h * K$ (1)

Vc is the cutting speed and is calculated as $Vc = 60 * \frac{l}{t}$ (2)

Where l is the cutting length of one run in mm and t is the time of cut for that run in seconds.

MRR is calculated in terms of mm3/min and Vc is calculated in terms of mm/min.

2. Determination of surface roughness and Kerf width

Surface roughness determines the quality of the surface after machining. It is a component of surface texture. If the deviations are more, surface is rough and if they are small, surface is smooth. The removed material undergoes a roughness test determining the cutting quality and how good is the surface finish after cutting operation. The surface roughness is measured by Talysurf instrument. Kerf width determines the width of the removed material during cutting operation. The diameter of the wire should be always greater than or equal to the kerf width. After the machining operation, the work-piece is scanned under optical microscope and by the help of suitable software; the required kerf-width can be measured.

IV. ANALYSIS OF RESULT

The experimented was conducted and the various output results obtained were analysed for further experiments. The roughness, Kerf width and MRR were calculated using different processes and in order to achieve a good result, the MRR should be maximized and the kerf width and surface roughness should be minimized.

A. Optical images of the cut gear

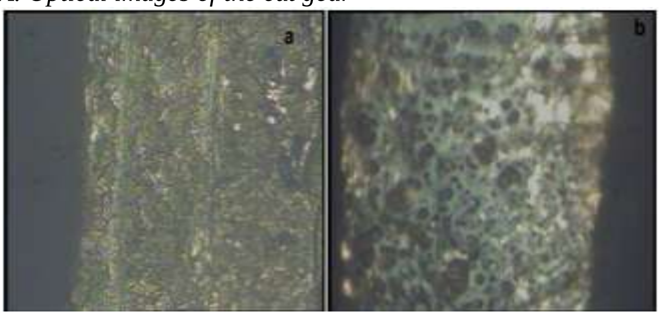

Figure 3: Optical images of the gear at a: 40 X zoom and b: 100X zoom

Figure 3 shows the optical image of the cut gear before polishing at 40 X and 100 X zoom. The cut gear is placed under microscope and only the edges are scanned and studied as all the micro-structural analysis occurs near the surface of the cutting in wire EDM.

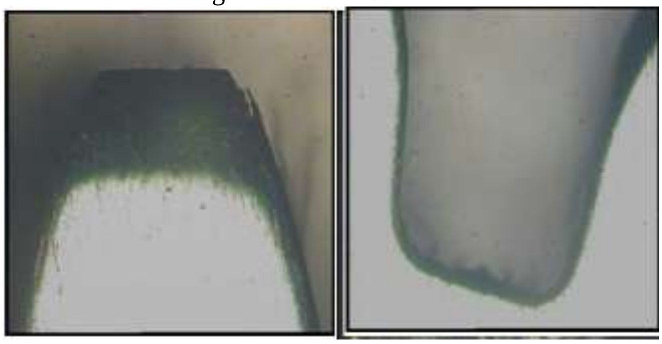

Figure 4: Optical images of the gear after polishing at 100X zoom

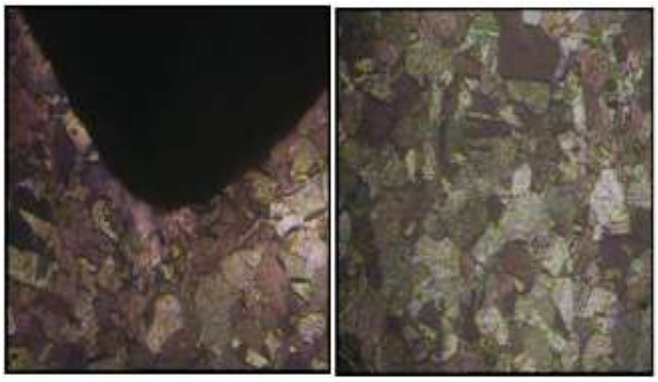

Figure 5: Optical images of the gear after etching at 100X zoom

Figure 5 illustrates some of the grain structures appeared during machining of copper plate at 100X optical zoom after etching. The etchants used is distilled water and nitric acid.

B. Energy Dispersive Spectroscopy of copper

Energy Dispersive X-ray spectroscopy also called as EDX is used for analyzing chemical characteristics of a sample. Table 4 depicts EDS of a copper plate and it is concluded that carbon weight percentage is found to be 20.69 and copper weight percentage is found to be 79.31 in the kth cell.

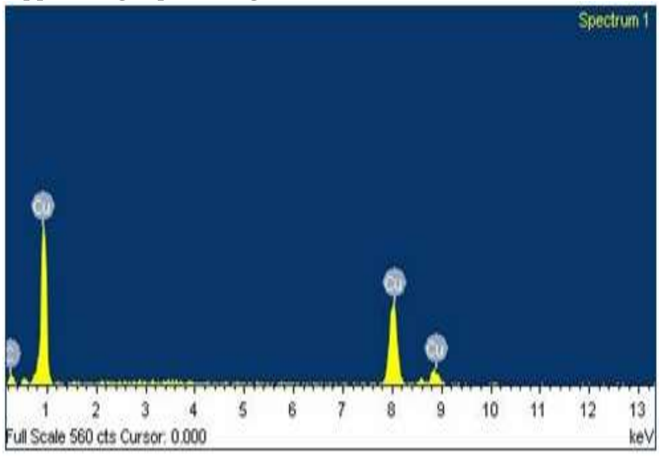

Figure 6: EDS of a copper plate

Table 4: EDS of a copper plate

Element	Weight %	Atomic %
C K	20.69	57.99
Cu K	79.31	42.01
Total	100	

C. SEM image of copper material used for the gear

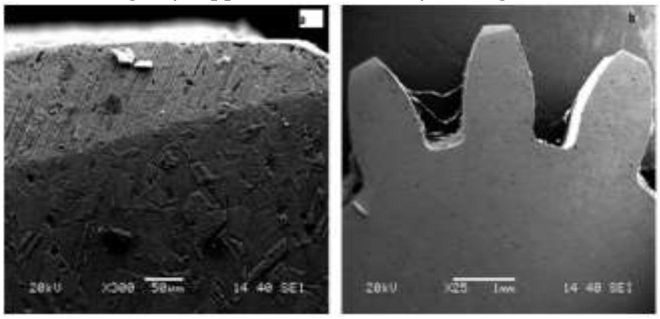

Figure 7: SEM image of wire EDM cut surface at a: 300X and b: 25X

Figure 7 shows SEM images of the miniature gears manufactured at optimal parameters and from the figure it is clear that the miniature gears have burr free uniform tooth profile.

V. MULTI-OBJECTIVE OPTIMIZATION OF PARAMETERS USING DESIRABILITY WITH PCA

Optimization is a method to find out the most suitable and best values from the given set of results. The present work focuses on optimizing the response parameters by maximizing the MRR and minimizing the surface roughness and kerf width.

Table 5: Multi objective optimization of response parameters

Sl Number	Normalized values (N_{ij}) MRR	Ra	Kerf Width	Combined Quality loss (CQL)
1	0.369	0.370	0.714	0.515
2	0.157	0.348	0.761	0.577
3	0.110	1	0.666	0.408
4	0.591	0	0.285	0.707
5	0.245	0.269	0.857	0.543
6	0.137	0.168	1	0.564
7	0	0.876	0	0.708
8	1	0.528	0.380	0.364
9	0.562	0.719	0.190	0.509

A. Steps involved in calculating Desirability with PCA

The Desirability function is given as

$$\text{For Higher the better, } d_r \max = \begin{cases} 0 & \text{if } y \le y_{min} \\ \left(\frac{y - y_{min}}{y_{max} - y_{min}}\right)^r & \text{if } y_{min} \le y \le y_{max} \\ 1 & \text{if } y \ge y_{max} \end{cases} \quad (3)$$

$$\text{For Lower the better, } d_r \min = \begin{cases} 1 & \text{if } y \le y_{min} \\ \left(\frac{y - y_{max}}{y_{min} - y_{max}}\right)^r & \text{if } y_{min} \le y \le y_{max} \\ 0 & \text{if } y \ge y_{max} \end{cases} \quad (4)$$

Here r is the desirability index function which is taken as 1. y is the undesirable value. The values of y_{max} and y_{min} are chosen by the user.

After the normalization, the next step is to find out the correlation using PCA. The steps involved in principal Component analysis are **a**. Normalization of process parameters **b**. finding out the Pearsons Correlation Coefficients **c**. Finding out the individual PCA and **d**. Calculation of Multiple Performance Index (MPI) and **e.** Calculation of combined Quality Loss (CQL).

VI. RESULT AND DISCUSSIONS

A. Effect of process parameters on CQL

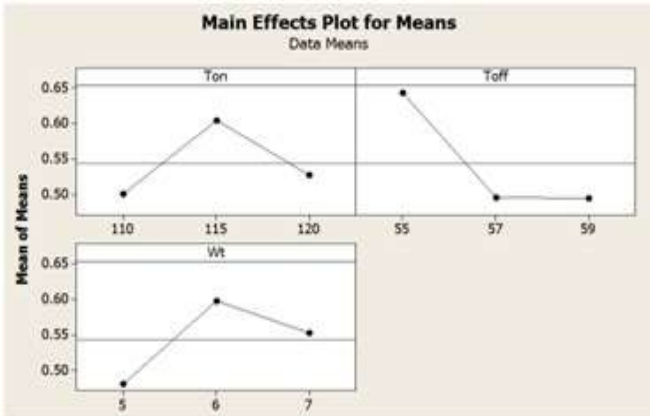

Figure 8: Main effect plot for combined quality loss

Figure 8 shows the main effect plot diagram for various process parameters. Highest value in the graph indicates the optimal values for the combined sets. From the figure it is clear that the highest values for TON, TOFF and WT occur at 115µs 55µs and 6 Kg-f. The combination is 115-55-6 which is present at run 4 of Table 3. The corresponding values of MRR, Ra and Kerf width are 2.347, 2.67 and 0.266 respectively and are the optimum result for the given set. It is also seen from the figure that with the increase in the Pulse on time, the overall response parameters i.e. CQL increase and then decreases. Similarly with the increase in pulse off time, the CQL gradually decreases and attains a constant value and with the increase in wire tension the CQL increase and then decreases. The variation in the graph is due to the sudden change in voltage and current resulting in variation in cutting speed and different sources of error according to the environmental condition which is otherwise called a signal to noise ratio.

B. Graphs and plots obtained and its effect on CQL

Figure 9 depicts various plots obtained from experimentation. Figure 9(a) is the standard residual plot obtained and the points more close to the line indicates best results. The normal

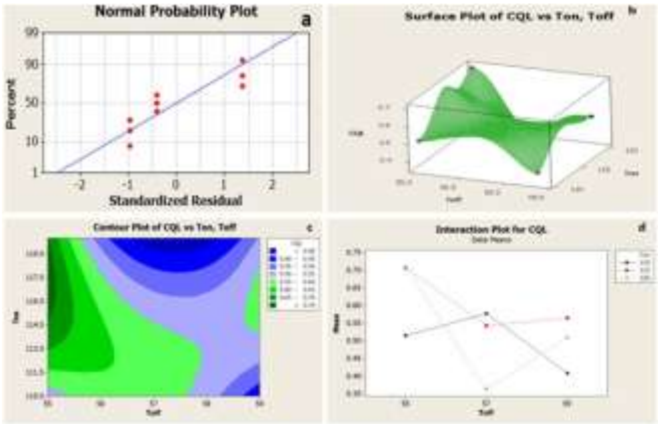

Figure 9: Various plots obtained for different parameters a: Residual plot; b: Surface plot; c: Contour plot; d: Interaction plot

Probability plot is a graphical technique indicating whether the data set is normally distributed or not. Figure 9(b) determines the *surface plot* of CQL with pulse on time and off time. Darker regions in the surface plot indicates high CQL values and from the figure it is clear that darker regions occur at the Pulse on time 115µs and Pulse off time 57µs. Figure 9(c) shows the *contour plot* of CQL with Pulse on time and Pulse off time. The relation between the variables can be seen in the contour plot. The contour plot reveals that the CQL is highest in the Pulse on time 115µs and 57µs. Figure 9(d) shows the *interaction plot* between T_{ON} and T_{OFF}. The interaction plot revels that there is an interaction between pulse on time 115µs and pulse off time 55µs. Interaction plots are often used to know the interactions during ANOVA. The interaction is due to the fact that the output responses and the input responses are not parallel for a given set of results.

Table 6: ANOVA Table for means

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
TON	2	0.01772	0.01772	0.0088	0.71	0.584
TOFF	2	0.04450	0.04450	0.0222	1.79	0.035
WT	2	0.02079	0.02079	0.0103	0.83	0.545
Residual Error	2	0.02491	0.02491	0.0124		
Total	8	0.10792				

ANOVA table tells us which factor is significantly affecting the responses. P denotes the probability value. If the P value is less than 0.05, the factor is said to be significant. From Table 6, it is clear that Pulse off time is the significant factor and it contributes the most during the prediction of output responses.

Table 7: Response Table for means

Level	T_{ON}	T_{OFF}	W_T
1	0.500	0.6433	0.481
2	0.604	0.494	0.597
3	0.527	0.493	0.553
Delta	0.104	0.149	0.116
Rank	3	1	2

Table 7 predicts the rank of the input parameter for the experiment. From the response table the most significant input parameter for the experiment is Pulse off time followed by Wire tension and Pulse on time. Pulse off time plays a significant role in optimizing the output responses.

VII. CONCLUSION

The following paper describes the optimization of process parameters using desirability with PCA technique. From the main effect plot graph it was observed that the best combinations occur at TON 115µs, TOFF 55µs and wire tension at 6 Kg-f. The corresponding values of MRR, Ra and Kerf width were at 2.347, 2.67 and 0.266 respectively which is said to be the optimum achieved output results. From the ANOVA table, Pulse off time is found to be highly significant factor in which the P value was found to be 0.035 followed by wire tension and Pulse on time. The maximum material removal occurs at high pulse off time and low pulse on time. The variation in the kerf width is due to change in the voltage and current at different peaks.

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